Cognition 123 (2012) 380–391

Contents lists available at SciVerse ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Incidental sequence learning across the lifespan

Brigitte Weiermann, Beat Meier *

Department of Psychology & Center for Cognition, Learning and Memory University of Bern, Bern, Switzerland

ARTICLE INFO

Article history:
Received 28 April 2011
Revised 21 February 2012
Accepted 21 February 2012
Available online 17 March 2012

Keywords:
Implicit learning
Task sequence learning
Development
Aging

ABSTRACT

The purpose of the present study was to investigate incidental sequence learning across the lifespan. We tested 50 children (aged 7–16), 50 young adults (aged 20–30), and 50 older adults (aged >65) with a sequence learning paradigm that involved both a task and a response sequence. After several blocks of practice, all age groups slowed down when the training sequences were removed, providing indirect evidence for sequence learning. This performance slowing was comparable between groups, indicating no age-related differences. However, when explicit sequence knowledge was considered, age effects were found. For both children and older adults with no or only little explicit knowledge, incidental sequence learning was largely reduced and statistically not significant. In contrast, young adults showed sequence learning irrespective of the amount of explicit knowledge. These results indicate that different learning processes are involved in incidental sequence learning depending on age.

1. Introduction

The ability to incidentally learn complex information and regularities which are present in the physical and social environment is fundamental from early childhood to old age. For example, incidental learning is involved in language acquisition or skill learning such as learning to ride a bike, learning to play a musical instrument or learning to typewrite. Furthermore, our daily routine is determined by repeating sequences of actions. For example, we wake up in the morning by the sound of the radio. We get up, go to the bathroom and take a shower. After getting dressed, we prepare our breakfast in the kitchen by starting the coffee machine and we slice bread while waiting for the coffee to be ready. The predictable flow of these actions can facilitate performance. However, if these series are disrupted (e.g., if the coffee machine is out of order) then performance may be decelerated. The purpose of the present study was to investigate incidental learning of sequenced regularities across the lifespan. Specifically, we tested children (aged 7–16), young adults (aged 20–30) and older adults (aged over 65) with a sequence learning paradigm. To our knowledge, this is the first incidental sequence learning study including both children and older adults.

Typically, the serial reaction time task (SRTT; Nissen & Bullemer, 1987) is used to investigate incidental sequence learning. In this task, participants are required to respond to a stimulus that appears at one of four locations on the screen by pressing a corresponding key. Unbeknownst to them, the stimulus location (and, thus, the motor response) is determined by a repeating sequence. During several blocks of practice, response times usually decrease. When the sequence is removed and stimuli are presented randomly, response times typically increase. This increase in response time is taken as indirect evidence of incidental or implicit sequence learning. Incidental sequence learning may also create explicit sequence knowledge, that is, participants may, or may not, become consciously aware of what they have learned (for a debate on consciousness in incidental sequence learning, see for example Perruchet & Amorim, 1992; Rünger & Frensch, 2010; Shanks & St. John, 1994).

---

* Corresponding author. Address: Department of Psychology, Muesmattstr. 45, 3000 Bern 9, Switzerland. Tel.: +41 31 631 40 39; fax: +41 31 631 82 12.

E-mail address: beat.meier@psy.unibe.ch (B. Meier).

0010-0277/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.cognition.2012.02.010

Only few studies have investigated developmental differences in incidental sequence learning during childhood and adolescence. In the first SRTT study with children, Meulemans, Van der Linden, and Perruchet (1998) found neither differences in incidental sequence learning nor in explicit knowledge between 6-year olds, 10-year olds and young adults. Furthermore, all three age groups retained the sequence knowledge after a 1-week delay. These results indicate that incidental sequence learning is present as early as in 6-year olds and they suggest that it may remain invariant throughout childhood. In fact, this was found by Karatekin, Marcus, and White (2007) who investigated two groups of children (8–10 year olds and 11–13 year olds), a group of adolescents (14–17 year olds) and a control group of young adults (>18 year olds).

Thomas and Nelson (2001) also observed equivalent incidental sequence learning and no difference in explicit knowledge in 7-year olds and 10-year olds. However, although RT measures of sequence learning did not differ between age groups, increasing anticipatory responses were observed with increasing age. This suggests that older children learned more about the sequence than younger children. In a second experiment, Thomas and Nelson (2001) found evidence for incidental sequence learning in 4-year olds. They used another version of the SRTT which complicates a direct comparison between all three age groups. However, 4-year olds showed even less anticipatory responding and more of them failed to demonstrate any sequence learning. Thus, their results suggest that a developmental change occurs in incidental sequence learning during childhood. Further support for this hypothesis was provided by a study using functional magnetic resonance imaging (fMRI; Thomas et al., 2004). In this study, 7- to 11-year olds showed less sequence learning than young adults. Furthermore, age-related differences were observed in brain activity. Whereas children showed greater recruitment of subcortical motor structures (specifically the putamen), adults showed greater recruitment of cortical regions (including premotor cortex). This difference presumably reflects age differences in motor response execution. Further developmental differences were found in activations of regions of the inferotemporal cortex, the hippocampus, and the parietal cortex.

In sum, the few studies investigating children revealed inconsistent findings as to whether incidental sequence learning is subject to developmental change in childhood or not. Whereas some studies report age-invariant incidental sequence learning in children (e.g., Karatekin et al., 2007; Meulemans et al., 1998), others report age-related differences (e.g., Thomas & Nelson, 2001; Thomas et al., 2004; see also De Guise & Lassonde, 2001; Fischer, Wilhelm, & Born, 2007; Savion-Lemieux, Bailey, & Penhune, 2009).

In contrast to the sparse amount of studies with children, incidental learning in older age has been widely investigated. For example, using a SRTT, incidental sequence learning was found to be intact in older adults (mean age above 65 years) in several studies (e.g., Gaillard, Destrebecqz, Michiels, & Cleeremans, 2009; Howard & Howard, 1989, 1992; Salthouse, McGuthry, & Hambrick, 1999). However, these studies also found a decline in explicit knowledge in older adults. Similarly, intact incidental sequence learning and diminished explicit knowledge in older adults was found in an auditory variant of the SRTT without a motor response sequence (Dennis, Howard, & Howard, 2006, Experiments 1 and 2). Together, these studies suggest dissociative effects of aging on incidental sequence learning vs. explicit knowledge.

However, several other studies suggest a deficit in incidental sequence learning in older adults. Older adults were impaired at incidental sequence learning in a standard SRTT, irrespective of sequence structure (Curran, 1997) and in a spatial SRTT with hand posture sequencing (Harrington & Haaland, 1992). More recently, several studies investigated the effect of aging on incidental sequence learning using the alternating serial reaction time task (ASRTT). This procedure minimizes the emergence of explicit sequence knowledge, because only every second stimulus follows a predetermined sequence whereas the remaining stimuli are selected randomly (i.e., sequenced stimuli alternate with random stimuli). Older adults were impaired at incidental sequence learning in a spatial ASRTT (e.g., Howard & Howard, 2001, 1997; Howard, Howard, Japikse, et al., 2004; Howard, Howard, Dennis, Yankovich, & Vaidya, 2004) or in an auditory version of the ASRTT (Dennis et al., 2006, Experiment 3; Dennis, Howard, & Howard, 2003). No age-related differences in explicit knowledge were present in these ASRTT studies. Taken together, these findings indicate an age-related deficit in incidental sequence learning.

Two recent fMRI studies investigated age-related differences in brain activity during incidental sequence learning (Daselaar, Rombouts, Veltman, Raaijmakers, & Jonker, 2003; Rieckmann, Fischer, & Bäckman, 2010). When comparing young and older adults, Daselaar et al. (2003) found no differences in brain activity although the rate of learning was somewhat slower in older adults. Thus, they suggested that both age groups recruited a similar network of brain regions. In contrast, Rieckmann et al. (2010) reported intact incidental sequence learning in older adults but age-related differences in the activation of neural networks. Whereas sequence learning was associated with activation increases in the striatum and activation decreases in the medial temporal lobe (MTL) in young adults, older adults showed activation increases in both the striatum and the MTL. The authors concluded that the additional MTL recruitment in older adults may be compensatory (for a review, see Rieckmann & Bäckman, 2009). Similarly, Aizenstein et al. (2006) found age-related differences in brain activity in both striatal and prefrontal regions during concurrent implicit and explicit sequence learning. Specifically, older adults showed diminished activation in the right putamen but increased activity in other subregions of the striatum as well as greater activation in the left dorsolateral prefrontal cortex and diminished activation in the right dorsolateral prefrontal cortex. Together, these results suggest that cognitive aging is related to changes in neural networks (see also Simon, Vaidya, Howard, and Howard (2012) for similar results in implicit associative learning).

In sum, these results indicate that incidental sequence learning occurs in old age. Nevertheless, older adults are somewhat impaired at learning when compared to young adults. Furthermore, older adults typically show less explicit sequence knowledge. Even if older adults show intact performance it might be attributable to different processes, as indicated by age-related differences in the recruitment of neural networks (Rieckmann & Bäckman, 2009; Rieckmann et al., 2010). Moreover, inconsistent findings of intact or impaired incidental sequence learning in older adults may be attributed to methodological differences between studies and to differences between samples.

So far, developmental and aging studies indicate age-related changes in incidental sequence learning both in childhood and in aging. However, no previous study has investigated incidental sequence learning across the lifespan. The purpose of this study was to close this gap between developmental and aging studies by investigating children, young adults and older adults. We used a variant of the SRTT that involved a sequence of *stimulus categories* rather than a sequence of stimuli. The paradigm was adapted from previous incidental task sequence learning (TSL) studies (e.g., Cock & Meier, 2007; Meier & Cock, 2010). In the TSL paradigm, participants are typically required to respond to several intermixed binary-choice tasks. For example, they are required to respond to stimulus color on the first trial, to stimulus shape on the second trial, to stimulus size on the third trial, and so on. Unbeknownst to them, the order of *tasks* is determined by a repeating sequence. The task sequence is repeated during several blocks of trials, during which response times decrease. When the task sequence is removed, response times increase. This increase in response time is taken as indirect evidence of incidental learning of the task sequence. Previous studies have shown that incidental task sequence learning is dependent on the presence of two correlated streams of information. For example, sequence learning occurred when the task sequence was combined with a motor response sequence or with a sequence of stimulus locations (Cock & Meier, 2007; Meier & Cock, 2010) or when the task sequence was combined with a sequence of response-mappings (Weiermann, Cock, & Meier, 2010). In contrast, a single task sequence without a correlated sequence or a single response sequence was not learned (Cock & Meier, 2007; Meier & Cock, 2010; Weiermann et al., 2010). Thus, we used a correlated task and a response sequence in the present study.

We tested children (aged 7–16), young adults (aged 20–30) and older adults (aged over 65) with a paradigm adapted from Meier and Cock (2010, Experiment 1). The selection of age groups was based on previous studies showing an inverted u-shaped curve of performance in different cognitive functions across the lifespan with a peak of performance at young adulthood (for reviews on cognitive aging, see Hedden & Gabrieli, 2004; Salthouse, 2010). Furthermore, previous sequence learning studies have shown that young adults (aged 18–39) and middle-aged adults (aged 40–59) perform similarly on the SRTT (Gaillard et al., 2009; Salthouse et al., 1999; but see Feeney, Howard, & Howard, 2002, for evidence of impaired sequence learning in middle-aged adults) whereas age-related differences appear when older adults (aged >60) are included (e.g., Curran, 1997; Dennis et al., 2003; Howard & Howard, 1997, 2001; Howard, Howard, Japikse, et al., 2004). Thus, the young adults group was considered as an anchoring point to which we compared children on the one hand and older adults on the other hand. Due to the limited accessibility to children and older adults, we chose to subsume a relatively broad age range within these age groups. The purpose was to achieve a large sample size that allows for the post-hoc exclusion of participants with relevant explicit knowledge. Moreover, correlational analyses within each age group can be used to explore age-related differences within groups.

Participants were presented with three different categorical classification tasks (*animals*, *implements*, *and plants*). In each trial, a color photograph appeared at the center of the screen (see Fig. 1). When the photograph showed an animal, participants were required to decide whether it was a bird or a mammal. When an implement was shown, they were required to decide whether it was a musical instrument or a kitchen utensil. When a plant was shown, they were required to decide whether it was a tree or a flower. Unbeknownst to the participants, the order of tasks and the order of motor responses were determined by repeating sequences of six elements. In order to assess sequence learning, the training task sequence and the training response sequence were replaced by untrained sequences in a distractor block. If participants slowed down when the training sequence is removed, this would provide indirect evidence for incidental sequence learning. Explicit sequence knowledge was assessed with a verbal generation task and with a recognition task at the end of the experiment.

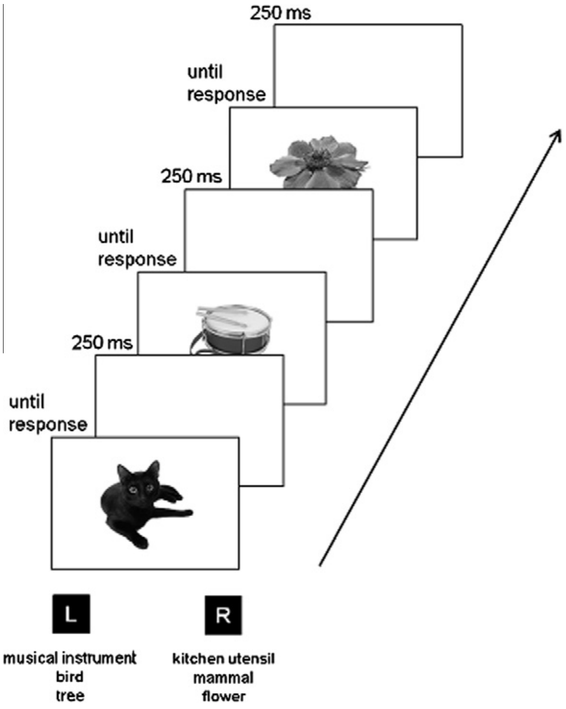

Fig. 1. Example of procedure and stimuli. Photographs were shown in color.

Table 1
Characteristics of the participants.

	Children	Young adults	Older adults
n	50	50	50
Age (years)	11.6 (4.1)	23.2 (2.3)	72.9 (7.0)
Gender (male:female)	17:33	15:35	23:27
Years of education	–	14.3 (1.8)	13.1 (3.4)
Estimated verbal IQ[a]	–	110.7 (11.8)	120.3 (14.2)
Forward digit span scores	7.1 (1.6)	7.8 (2.0)	6.4 (1.7)
Backward digit span scores	5.5 (2.1)	7.1 (2.2)	6.0 (1.8)
VST interference score[b]	1.9 (0.6)	1.7 (0.4)	2.1 (0.6)

Note: Standard deviations in parentheses.

[a] Verbal IQ was assessed by the MWT-A, a standardized German vocabulary test (Lehrl, Merz, Burkhard, & Fischer, 1991).

[b] VST: Victoria Stroop Test (Regard, 1981). Interference scores were calculated as the number of seconds required to name color words divided by the number of seconds required to name colored dots.

Our motivation to choose the TSL paradigm over the SRTT was twofold. First, the literature review suggests that age-related differences occur when task requirements are higher, for example by the use of more complex or alternating sequences (e.g., Curran, 1997; Dennis et al., 2006; Howard & Howard, 2001; Howard, Howard, Japikse, et al., 2004) or by the use of a secondary task (e.g., Frensch & Miner, 1994; see also Nejati, Garusi Farshi, Ashayeri, & Aghdasi, 2008). Hence, we would expect that the TSL paradigm would be more sensitive to detect developmental and age-related changes than the standard SRTT because it is more complex. In the SRTT, participants typically respond to visuo-spatial stimuli by pressing a spatially compatible response key. The task is relatively simple to perform as the stimulus-response mapping is straightforward and requires no higher-order cognitive processing. In contrast, in the TSL paradigm, each stimulus exemplar (e.g., the picture of a violin) has to be translated into a higher-order concept (e.g., musical instrument vs. kitchen utensil) in order to give the correct response. Furthermore, the sequence is not embedded in the order of stimuli but rather in the superordinate order of tasks or stimulus categories. Implicit task sequence learning has been established in young adults across a variety of different tasks, stimuli and sequences (Cock & Meier, 2007; Gotler, Meiran, & Tzelgov, 2003; Heuer, Schmidtke, & Kleinsorge, 2001; Koch, 2001; Koch, Philipp, & Gade, 2006; Meier & Cock, 2010; Weiermann et al., 2010). However, no previous TSL study has included children or older adults. Thus, a further goal was to provide insights into the trajectory of task sequence learning across the lifespan.

Second, the TSL paradigm has more ecological validity than the SRTT. On the one hand, the TSL paradigm involves different tasks and stimuli and is, therefore, more interesting both for children and adults to perform than the classical SRTT. This is important as it ensures that participants – especially younger children – remain focussed and motivated during the experiment. On the other hand, our daily routine involves numerous repeating sequences of actions. For example, the way we prepare a coffee may be broken down into several small steps of getting a cup out of the cupboard, adding coffee powder to the coffee machine, starting the machine by pressing a key, waiting for the cup to be filled, adding sugar and milk and stirring the coffee with a spoon. Although we may not always be aware of the rigid routine that drives these small steps, we perform these actions usually in a certain order.

2. Method

2.1. Participants

Fifty *children* aged between 7 and 16 years, 50 *young adults* aged between 20 and 30 years, and 50 *older adults* aged over 65 years (range 65–90) participated in this study. All participants were sampled from the circle of acquaintances of the experimenters. Exclusion criterion for *older adults* was global cognitive deterioration as indicated by performance below a cut-off of 27 points ($M = 29.1$, $SD = 1.0$) on the Mini Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975). The study was approved by the local ethics committee and all participants gave informed consent. For minors, parental consent was obtained. The demographic information for each age group (*children*, *young adults*, and *older adults*) is summarized in Table 1.

Only for adults, education level and verbal intelligence quotient (IQ) were assessed (see Table 1). *Young adults* were more educated than *older adults*, as indicated by an independent samples *t*-test, $t(74.42) = 2.16$, $p = .034$. However, *older adults* scored higher on verbal IQ than *young adults*, $t(94.92) = 3.69$, $p < .001$. All participants completed the Victoria Stroop Test (VST; Regard, 1981) and a digit span test (forward and backward; Tewes, 2001). Age groups were compared in separate one-way analyses of variances (ANOVAs). For the VST, there was a significant difference between age groups in interference scores, $F(2,147) = 9.31$, $p < .001$. Post-hoc Tukey HSD tests revealed that *older adults* performed significantly worse than *young adults* ($p < .001$), whereas no other group difference was significant (all $ps > .05$). For the forward digit span, there was a significant difference between age groups, $F(2,147) = 6.64$, $p = 002$. Post-hoc Tukey HSD tests revealed that *older adults* performed significantly worse than *young adults* ($p = .001$), whereas no other group difference was significant (all $ps > .10$). For the backward digit span, there was also a significant difference between age groups, $F(2,147) = 7.50$, $p = .001$. Post-hoc Tukey HSD tests revealed that young adults performed significantly better than the two other age groups (all $ps < .035$), whereas *chil-*

dren and *older adults* were not different from each other ($p = .416$).

2.2. Material

Stimuli were digitized color photographs (350×350 pixels) for three different tasks (implements, animals, or plants). Implements belonged to the stimulus categories *musical instruments* or *kitchen utensils*, animals to *birds* or *mammals*, and plants to *trees* or *flowers*. The stimulus categories had 16 photographs each. Depending on tasks and trials, presentation of these exemplars varied at random. All stimuli were presented against a white background at the center of a laptop monitor. Left-hand (L) and right-hand (R) responses were given using two keys of the laptop keyboard. Previous research has shown that this kind of pictorial material is well suited for lifespan studies (Zimmermann & Meier, 2006).

Task order was sequenced according to one of two 6-element sequences, counterbalanced within age group ("plants–animals–implements–animals–plants–implements" and "implements–plants–animals–plants–implements–animals"). Additionally, response order was sequenced according to one of two 6-element sequences, counterbalanced within age group ("L–R–L–L–R–R" and "R–L–R–R–L–L"). The combination of a task sequence with a response sequence resulted in the presence of one of four stimulus category sequences (e.g., "tree-mammal-musical instrument-bird-flower-kitchen utensil"). In pseudo-random practice blocks, the order of tasks and responses was random with the following constraints: equal task frequency, equal response frequency, equal stimulus category frequency, no task repetitions, and maximally two response repetitions.

2.3. Procedure

Participants were tested individually. They were instructed to respond as quickly and as accurately as possible. They were not informed about the presence of any sequenced information. They responded by pressing the L key with their left index finger and the R key with their right index finger. For the *implements* task, they pressed the L key for a *musical instrument* and the R key for a *kitchen utensil*. For the *plants* task, they pressed the L key for a *tree* and the R key for a *flower*. For the *animals* task, they pressed the L key for a *bird* and the R key for a *mammal*. The category-response mapping information was continuously presented below the screen. Each stimulus remained on screen until the participant pressed a response key, followed by an interval of 250 ms before presentation of the next stimulus (see Fig. 1).

The experiment consisted of 8 blocks of 96 stimulus-response trials each. Blocks 1–2 were practice blocks with pseudo-random ordering in order to train participants on the category-response mapping. In blocks 3–6, the order of tasks and responses followed a sequence (repeated 16 times per block). In block 7, this training sequence was replaced by the appropriate counterbalancing sequence. In block 8, the training sequence was reinstated. After each block, an accuracy feedback was displayed on screen during 30 s. When the participant was ready, the experimenter initiated the next block by pressing a key.

After the test session, a structured interview was carried out to assess explicit knowledge of the various sequences. Participants were first asked about the possible presence of sequenced information (tasks, responses, and stimulus categories) and then had to verbally generate six elements of each of the sequence. They were asked to guess when not sure. The structured interview was then followed by a 12 trial recognition test. In the recognition test, participants responded as usually to a five-element sequence fragment on each trial, and afterwards indicated whether they thought the fragment had occurred previously or not. Additionally, they were asked to indicate their confidence level on a scale of 1 (unconfident) to 5 (confident). Six trials were consistent with the structure of the training sequence, and six trials were new fragments consisting of pseudo-random ordering of five elements. The pseudo-random fragments were statistically comparable to the fragments of the training sequence.

2.4. Data analysis

For RT analyses, trials on which errors were made, trials that followed an error, and the first 6 trials of each block were excluded. Median RTs per block and participant were computed for the three tasks separately, and then averaged per block and participant. For the recognition task analyses, recognition accuracy was defined as the proportion of correct responses (hits and correct rejections). *Slope* scores were computed to analyze the confidence ratings (Yates, 1994; also sometimes referred to as the Chan difference score in artificial grammar learning; cf., Dienes, 2008). *Slope* is defined as $f_1 - f_0$, where f_1 is the average confidence rating for correct decisions and f_0 is the average confidence rating for incorrect decisions (computed within each participant).

For all statistical analyses, an alpha level of .05 was used. Greenhouse-Geisser corrections are reported where appropriate and effect sizes are expressed as partial η^2 values.

3. Results

3.1. Response accuracy

Mean response accuracy (averaged from blocks 3 to 8) was .98 ($SE = .003$) for *children*, .99 ($SE = .002$) for *young adults*, and .99 ($SE = .002$) for *older adults*. Thus, all three age groups performed close to ceiling and no further analyses on accuracy rates were conducted.

3.2. Response times

RTs are shown in Fig. 2. In all age groups, RTs decreased with practice. The mean training score (i.e., the RT difference between block 3 and block 6) was 122 ms ($SE = 25$) for *children*, 133 ms ($SE = 23$ ms) for *young adults*, and 260 ms ($SE = 26$) for *older adults*. A two-factorial ANOVA with the within-subject factor block (blocks 3–6) and the

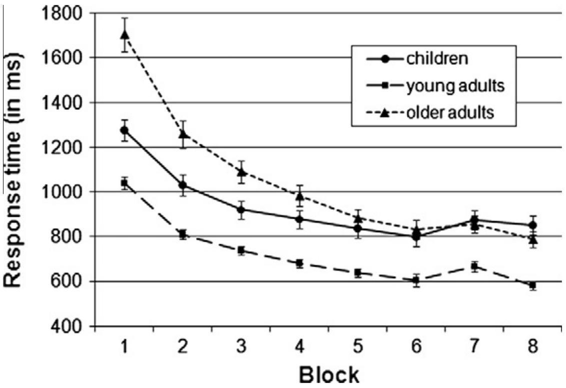

Fig. 2. Response time results for each age group separately. In Block 7, the training task sequence and the training response sequence were replaced by counterbalancing sequences. Error bars represent standard errors.

between-subjects factor age group (*children, young adults, older adults*) revealed a significant effect of block, $F(1.99,291.76) = 96.32$, $p < .001$, $\eta^2 = .40$, a significant effect of age group, $F(2,147) = 16.06$, $p < .001$, $\eta^2 = .18$, and a significant block × age group interaction, $F(3.97,291.76) = 7.16$, $p < .001$, $\eta^2 = .09$. Post-hoc Tukey HSD tests showed that *young adults* responded faster than both *children* and *older adults* ($ps < .01$), which in turn did not differ from each other ($p = .187$). To follow-up on the significant block × age group interaction, post-hoc Tukey HSD tests on training scores revealed that *older adults* showed significantly more RT improvement across blocks than both *children* and *young adults* ($ps < .01$). *Children* and *young adults* did not differ in their training scores ($p = .946$). It is apparent in Fig. 2 that *older adults* responded more slowly at the beginning of the experiment which allowed for more general RT improvement across blocks.

Sequence-specific learning was assessed by removing the training sequence in block 7. The mean disruption score (i.e., the difference between performance at block 7 and mean performance at blocks 6 and 8) was 50 ms ($SE = 13$) for *children*, 75 ms ($SE = 21$) for *young adults*, and 45 ms ($SE = 15$) for *older adults*. A two-factorial ANOVA with the within-subject factor block (block 7 vs. mean of blocks 6 and 8) and the between-subjects factor age group (*children, young adults, older adults*) revealed a significant effect of block, $F(1,147) = 35.44$, $p < .001$, $\eta^2 = .19$, indicating that participants were disrupted when the training sequence was removed in block 7. The effect of age group was also significant, $F(2,147) = 12.56$, $p < .001$, $\eta^2 = .15$. Again, post-hoc Tukey HSD tests revealed that *young adults* responded significantly faster than both *children* and *older adults* ($ps < .001$), which in turn did not differ from each other ($p = .930$). Importantly, the block × age group interaction was not significant, $F(2,147) = 0.91$, $p = .404$, $\eta^2 = .01$, indicating similar sequence-specific learning effects across age groups. Separate one-sample *t*-tests confirmed that the disruption scores of all age groups were significantly different from zero, with $t(49) = 3.87$, $p(\text{one-tailed}) < .001$ for *children*, $t(49) = 3.64$, $p(\text{one-tailed}) < .001$ for *young adults*, and $t(49) = 3.00$, $p(\text{one-tailed}) = .002$ for *older adults*.

Next, correlational analyses were used to explore the relationship between age and disruption scores within each age group. No significant correlations were found, with Pearson's $r = -.255$ ($p = .074$) for *children*, $r = .088$ ($p = .544$) for *young adults*, and $r = -.123$ ($p = .395$) for *older adults*.

3.3. Baseline RT differences between groups

To control for baseline RT differences between age groups, proportional disruption scores [(block 7 minus mean of blocks 6 and 8)/(block 7 plus mean of blocks 6 and 8)] were calculated for each subject separately (cf., Meulemans et al., 1998; Thomas & Nelson, 2001). The mean proportional disruption score was .03 ($SE = .01$) for *children*, .06 ($SE = .02$) for *young adults*, and .04 ($SE = .01$) for *older adults*. A one-way ANOVA on proportional disruption scores revealed no difference between age groups, $F(2,147) = 2.09$, $p = .127$.

3.4. Explicit knowledge

In the structured interview, 35 *children*, 35 *young adults*, and 39 *older adults* reported that they had noticed a response sequence; 24 *children*, 30 *young adults*, and 36 *older adults* reported that they had noticed a stimulus category sequence; and 17 *children*, 19 *young adults*, and 24 *older adults* reported that they had noticed a task sequence. One experimenter did not ask participants to verbally generate the specific sequence when they reported that they did not notice its presence. This concerned 12 participants who failed to notice at least one of the three sequences. For the remaining participants, the mean number of correctly generated elements of each sequence was calculated. The relative frequency distribution (proportion of correctly generated elements) is shown separately for each sequence type in Fig. 3.

Age-related differences in explicit knowledge were assessed in one-way ANOVAs with age group as between subjects factor for each sequence type separately. For the response sequence, the mean number of correctly generated elements was 5.1 ($SE = .12$) for *children*, 5.3 ($SE = .13$) for *young adults*, and 4.9 ($SE = .14$) for *older adults*. The one-way ANOVA revealed a marginally significant effect, $F(2,144) = 2.44$, $p = .091$. Post-hoc Tukey HSD tests showed a tendency for *older adults* to generate fewer sequence elements compared to *young adults* ($p = .073$). For the stimulus category sequence, the mean number of correctly generated elements was 2.8 ($SE = .23$) for *children*, 3.4 ($SE = .25$) for *young adults*, and 2.6 ($SE = .22$) for *older adults*. The one-way ANOVA revealed a significant effect, $F(2,142) = 3.35$, $p = .038$, and post-hoc Tukey HSD tests showed that *older adults* generated significantly fewer correct sequence elements than *young adults* ($p = .038$), whereas no other group difference was significant ($ps > .10$). For the task sequence, the mean number of correctly generated elements was 3.9 ($SE = .16$) for *children*, 4.2 ($SE = .20$) for *young adults*, and 3.4 ($SE = .17$) for *older adults*. There was a significant effect of age group, $F(2,135) = 4.23$, $p = .017$. Again, post-hoc Tukey HSD tests showed that *older adults* generated significantly fewer cor-

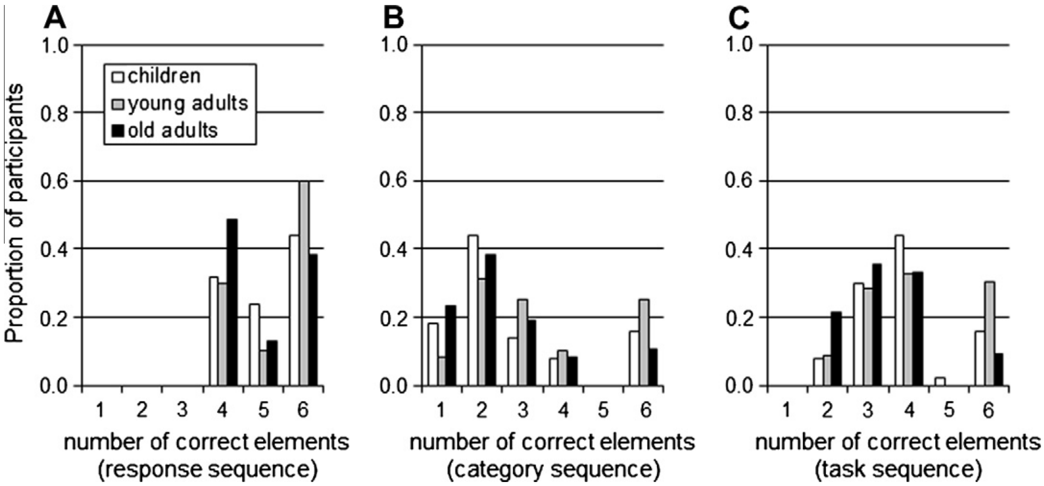

Fig. 3. Proportion of correctly generated elements of (A) the response sequence, (B) the stimulus category sequence, and (C) the task sequence separately for each age group.

rect sequence elements than *young adults* ($p = .013$), and no other group differences ($ps > .15$).

In the recognition test, the data of one *young adult* is missing due to a technical error. Mean recognition accuracy was .58 ($SE = .03$) for *children*, .60 ($SE = .03$) for *young adults*, and .59 ($SE = .02$) for *older adults*. A one-way ANOVA revealed no significant effect of age group, $F(2,146) = 0.23$, $p = .798$. For each age group separately, recognition accuracy was compared to chance level performance in separate one-sample *t*-tests against a test value of 0.50. All age groups performed above chance in the recognition test, with $t(49) = 3.066$, $p = .004$ for *children*, $t(48) = 3.926$, $p < .001$ for *young adults*, and $t(49) = 3.726$, $p = .001$ for *older adults*. For the confidence ratings, s*lope* was .16 ($SE = .08$) for *children*, .15 ($SE = .08$) for *young adults*, and .20 ($SE = .07$) for *older adults*. A one-way ANOVA revealed no significant difference between groups, $F(2,143) = 0.12$, $p = .887$.

In order to investigate whether the sequence-specific learning effect was attributable to explicit knowledge, the disruption scores were computed separately for high-explicit and low-explicit participants. Performance in the structured interview was taken as indicative of either high or low explicit sequence knowledge. The relative frequency distribution of correctly generated sequence elements showed a bimodal distribution with one peak at six elements (high-explicit) and another peak clearly below five elements, depending on the type of sequence (Fig. 3). The border between the two peaks was at five elements. Thus, participants were classified as high-explicit if they generated at least one sequence completely (six elements), whereas the remaining participants were classified as low-explicit. Importantly, the exclusion of borderline cases who generated five elements of any one of the sequences did not affect the statistical outcomes. Therefore, we included all cases for the analyses reported here. Within each age group separate independent-samples *t*-tests confirmed that high-explicit and low-explicit participants differed with regard to explicit knowledge of both the response and the stimulus category sequence (all $ps < .01$). For the task sequence, the difference in explicit knowledge was significant in *young adults* ($p = .002$), marginally significant in children ($p = .058$), but not significant in older adults ($p = .211$). Thus, within each age group high-explicit and low-explicit participants differed with regard to explicit knowledge of at least two sequences. Importantly, among low-explicit participants there was no significant age difference in explicit knowledge of the three sequences, as indicated by separate one-way ANOVAs (all $ps > .131$).[1]

The mean disruption scores of high-explicit and low-explicit participants are shown in Table 2 for the three age groups separately. We tested whether the disruption scores were significantly different from zero in separate one-sample *t*-tests for each age group. This was the case for high-explicit participants irrespective of age group, with $t(27) = 4.08$, $p(\text{one-tailed}) < .001$ for *children*, $t(30) = 3.02$, $p(\text{one-tailed}) = .003$ for *young adults*, and $t(20) = 3.11$, $p(\text{one-tailed}) = .003$ for *older adults*. With regard to low-explicit participants, only the disruption score of *young adults* was significantly different from zero, $t(18) = 2.07$, $p(\text{one-tailed}) = .027$. The other two age groups did not differ from zero, with $t(22) = 1.51$, p(one-

---

[1] In order to test whether explicit knowledge of the low-explicit participants was above chance, we compared their generation performance with a random control group from a previous study in which participants performed the same tasks and procedure with the exception that stimuli were written words rather than photographs (Meier & Cock, 2010, Experiment 1). Task order (sequenced vs. random) and response order (sequenced vs. random) were manipulated orthogonally, resulting in four between subjects conditions. For the control group with no sequences, the mean number of correctly generated elements was 4.8 ($SE = 0.1$) for the response sequence, 1.9 ($SE = 0.1$) for the stimulus category sequence, and 3.4 ($SE = 0.2$) for the task sequence. For low-explicit participants in the present study, the mean number of correctly generated elements was 4.3 ($SE = 0.1$) for the response sequence, 2.2 ($SE = 0.2$) for the stimulus category sequence, and 3.4 ($SE = 0.01$) for the task sequence. Low-explicit participants generated significantly less elements of the response sequence ($p < .001$), significantly more elements of the stimulus category sequence ($p = .049$), and did not differ from the control group in the generation of the task sequence ($p = .966$). Thus, overall, the low-explicit participants of the present study showed chance level performance.

Table 2
Disruption scores of high-explicit and low-explicit participants.

	Low-explicit participants		High-explicit participants	
	M (*SE*)	*n*	*M* (*SE*)	*n*
Children	31 (20)	23	67 (16)*	27
Young adults	52 (25)*	19	89 (29)*	31
Older adults	14 (13)	29	88 (28)*	21

Note: Participants were classified as high-explicit if they generated at least one sequence correctly in the structured interview.
* $p < .05$.

tailed) = .073 for *children*, and $t(28) = 1.02$, p(one-tailed) = .158 for *older-adults*. Thus, *young adults* showed sequence-specific learning effects even if participants with high explicit knowledge were excluded from the analysis. In contrast, in *children* and *older adults* sequence learning was largely reduced when participants with high explicit knowledge were excluded and was not anymore statistically significant.

4. Discussion

The purpose of this study was to investigate incidental sequence learning across the lifespan. We tested children, young adults and older adults in a sequence learning paradigm involving a task sequence and a correlated response sequence (cf., Cock & Meier, 2007; Meier & Cock, 2010). Overall, young adults responded faster than both children and older adults. Older adults showed more general response time improvement across the first four sequenced blocks (blocks 3–6). However, this enhanced general practice effect was probably attributable to the fact that older adults started considerably more slowly than both younger age groups. More importantly, all age groups slowed down when the training task sequence and response sequence were replaced by untrained sequences, thus providing evidence for sequence learning. The three age groups did not differ with regard to this increase in response time, indicating no age-related differences in incidental sequence learning at first glance.

However, with regard to explicit knowledge, age-related changes were found in the sequence generation task. Numerically, there was a tendency for children to show less explicit knowledge than young adults. However, this difference was statistically not significant, indicating no developmental change in explicit knowledge acquired during incidental sequence learning. In contrast, older adults generated significantly fewer elements of both the stimulus category sequence and the task sequence compared to young adults. There was also a tendency for older adults to generate fewer correct response sequence elements than young adults. Thus, the sequence generation task generally revealed a decline in explicit knowledge in older adults.

Comparing the performance of participants with complete and with little explicit sequence knowledge revealed age-related differences. Irrespective of age group, participants who were able to generate a complete sequence showed evidence of sequence learning as indicated by their slowing when the training sequence was removed. In contrast, the three age groups with little or no explicit sequence knowledge differed considerably. Whereas evidence for sequence learning was found in young adults, sequence learning was at least largely reduced to the point of non-significant learning in children and older adults. Thus, in children and older adults, sequence learning seemed to be restricted to participants with explicit knowledge.

It seems that children and older adults were not able to learn the complex regularities *implicitly*, that is, without conscious awareness of the sequences. They learned the sequences only in combination with substantial explicit knowledge. This suggests that they relied on explicit knowledge in order to compensate for a learning deficit. This absence of *implicit* sequence learning is in contrast to previous studies reporting intact sequence learning in children and older adults (e.g., Daselaar et al., 2003, 2006, Experiments 1 & 2; Gaillard et al., 2009; Howard & Howard, 1989, 1992; Karatekin et al., 2007; Meulemans et al., 1998). It is consistent with studies reporting an attenuation of sequence learning in children and older adults rather than its complete absence (e.g., Curran, 1997; Dennis et al., 2003; Harrington & Haaland, 1992; Howard & Howard, 1997; Howard, Howard, Japikse, et al., 2004; Howard, Howard, Dennis, et al., 2004; Thomas & Nelson, 2001; Thomas et al., 2004). However, in part our findings might be related to the particular TSL paradigm used in the present study.

4.1. TSL theories

The present TSL paradigm involved three different correlated sequences (a task sequence, a response sequence and a stimulus category sequence), each of which could have driven sequence learning. Performance in the sequence generation task suggests that the response sequence was more easily learned than the two other sequences. However, the response sequence was also more easily generated correctly by chance than the other sequences in random control conditions with no sequences from previous studies (Cock & Meier, 2007; Meier & Cock, 2010). Furthermore, previous studies have shown that the response sequence used in the present study was not learned unless it was correlated with either a sequence of tasks or of stimulus locations (Cock & Meier, 2007; Meier & Cock, 2010). Thus, it seems highly unlikely that learning in this TSL paradigm was solely based on the response sequence.

In general, three different explanations have been proposed on what implicit sequence learning in a TSL paradigm may be based. The first explanation holds that participants learn a sequence of repeating perceptual stimulus features (Heuer et al., 2001). The second explanation suggests that implicit task sequence learning is based on automatic task-set activation (Koch, 2001), that is, an unspecific automatic priming of task sets. According to the third explanation, correlated streams of information are necessary for implicit task sequence learning to occur – irrespective of the kind of information (Meier & Cock, 2010). For example, task sequence learning effects were found when a task sequence was correlated with a response sequence, with a stimulus location sequence or with a sequence of stimulus-response mappings (Cock & Meier, 2007; Meier & Cock, 2010; Weiermann et al., 2010). In a previous study, we have shown that the third explanation can account for patterns of results that cannot be accounted for by either perceptual learning or automatic task set activation (Weiermann et al., 2010). Therefore, in the TSL paradigm used in the present study, learning most probably is based on the integration of the task and the response sequence.

Hence, in contrast to perceptuo-motor learning in the SRTT, the TSL paradigm involves the integration and learning of more abstract higher-order information. That is, there is no sequence of stimuli but a sequence of superordinate tasks or stimulus categories (e.g., "tree-mammal-musical instrument-bird-flower-kitchen utensil"). Learning such information might be more difficult than learning the perceptuo-motor sequences in the SRTT. Thus, it is possible that differences in the complexity of the to-be-learned sequenced material might affect children and older adults more than young adults.

This consideration is supported by several studies. First, the sequence learning deficit in older adults manifests more clearly with increasing sequence complexity. Whereas older adults seem to learn simple deterministic sequences with predictive pairwise information as well as do young adults (e.g., Howard & Howard, 1989, 1992), age-related deficits are found with more complex sequences (e.g., Curran, 1997) or with the alternating sequences used in the ASRTT (e.g., Dennis et al., 2006, Experiment 3, 2003; Howard & Howard, 2001, 1997; Howard, Howard, Japikse, et al., 2004; Howard, Howard, Dennis, et al., 2004). Second, age deficits in incidental sequence learning emerge when the task is relatively difficult. For example, older adults were impaired at incidental learning of hand posture sequences in a modified SRTT (Harrington & Haaland, 1992). This task required participants to translate the stimulus cues into more complex hand postures rather than simply pressing a spatially compatible button. Third, sequence learning was impaired in older adults under dual-task conditions but not under single task conditions (Frensch & Miner, 1994; Nejati et al., 2008). Thus, the relative complexity of the sequenced information in the present study may explain the lack of sequence learning in absence of explicit knowledge in older adults. We assume that the same reasoning holds for the learning deficit in children. However, further research is needed to investigate this assumption as the few studies with children do not allow for drawing firm conclusions yet.

4.2. Neuropsychological considerations

The present findings indicate that children and older adults may have compensated an implicit sequence learning deficit with explicit knowledge and that incidental sequence learning draws on different processes across the lifespan. Young adults rely more on implicit learning processes than both children and older adults and, therefore, different neural networks are involved (e.g., Dennis & Cabeza, 2011; Rieckmann & Bäckman, 2009; Rieckmann et al., 2010). Although no consensus on the exact neural substrate of implicit sequence learning has been reached yet, the recruitment of a fronto-striatal network has been indicated by the majority of neuroimaging studies investigating young adults (e.g., Destrebecqz et al., 2005; Grafton, Hazeltine, & Ivry, 1995, 1997, 1998; Rauch et al., 1997) and by numerous clinical studies with neurological patients with damage to fronto-striatal regions (e.g., Exner, Koschack, & Irle, 2002; Gómez Beldarrain, Grafman, Pascual-Leone, & Garcia-Monco, 1999; Gómez Beldarrain, Grafman, Ruiz de Velasco, Pascual-Leone, & Garcia-Monco, 2002; Kim et al., 2004; Siegert, Taylor, Weatherall, & Abernethy, 2006; Vakil, Kahan, Huberman, & Osimani, 2000). In the context of healthy aging, Rieckmann and Bäckman (2009) proposed that impaired striatal function might be compensated by an increased reliance on extrastriatal regions such as the MTL and the frontal cortex during sequence learning. This hypothesis was supported by recent fMRI findings which showed that sequence learning was related to activation increases both in the striatum and the MTL in older adults. In contrast, sequence learning was related to activation increases in the striatum and activation decreases in the MTL in young adults (Rieckmann et al., 2010). This additional MTL recruitment in older adults was interpreted as reflecting compensatory neural activation during incidental sequence learning. Similarly, Dennis and Cabeza (2011) found that young adults showed differential recruitment of the striatum for implicit learning and the MTL for explicit learning whereas older adults did not. During implicit sequence learning, older adults showed less activity in the striatum but more activity in the bilateral hippocampus and the left dorsolateral prefrontal cortex than young adults. The authors suggested that this dedifferentiation of memory systems in older adults may represent a compensatory mechanism. Altogether, neuroimaging studies suggest that incidental sequence learning recruits different processes and neural networks depending on age. In line with these findings, the result that only young adults showed sequence learning in absence of explicit knowledge indicates that older adults relied on different learning processes than young adults.

Likewise, children may also have relied on different learning processes than young adults because the fronto-striatal network which underlies implicit sequence learning is not yet fully developed in children and young adolescents. Brain maturation between childhood and young adulthood involves a linear increase in white matter volume and nonlinear changes in cortical gray matter volume with a preadolescent increase followed by a postadolescent decrease (for reviews, see Lenroot & Giedd, 2006; Paus, 2005; Toga, Thompson, & Sowell, 2006). The changes in gray matter are regionally specific, with increases followed by volume loss occurring first in sensorimotor and last in higher-order association cortices such as the dorsolateral prefrontal cortex, the maturation of which continues until late adolescence (e.g., Giedd et al., 1999; Gogtay et al., 2004; Sowell, Trauner, Gamst, & Jernigan, 2002). Brain maturation between adolescence and young adulthood is localized within large regions of the frontal cortex and the basal ganglia (specifically the putamen and the globus pallidus), with relatively little change in any other region (Sowell, Thompson, Holmes, Jernigan, & Toga, 1999). Thus, gray matter of regions that are connected through fronto-striatal circuitry seems to be the last to mature. Furthermore, a recent diffusion tensor imaging study showed that white matter maturation in adolescence is primarily characterized by enhanced connectivity between cortical and subcortical regions, including the fronto-striatal circuitry (Asato, Terwilliger, Woo, & Luna, 2010). Therefore, children rely on different processes than young adults because of the ongoing maturation of the specific networks involved in implicit sequence learning. For example, Thomas et al. (2004) found differential neural activation patterns in children compared to adults during implicit sequence learning.

4.3. Lifespan approaches

So far, only few theoretical accounts have been put forward to explain *lifelong* changes in cognitive abilities (e.g., Baltes, 1987; Craik & Bialystok, 2006; Li & Baltes, 2006; Salthouse, 1996). For example, Salthouse (1985,1996) has proposed a processing-speed account for age-related differences in cognition. The speed with which many cognitive processes can be executed increases from infancy to young adulthood and then declines from the twenties to old age. The processing-speed account holds that this general slowing is supposed to be the primary cause of age-related differences in cognition. Two distinct mechanisms are postulated by which the slowing causes cognitive deficits: the *limited time mechanism* and the *simultaneity mechanism*. The limited time mechanism is based on the assumption that the time to perform later operations is restricted when the execution of early operations occupies a large proportion of the available time. That is, the slowing does not allow for complete processing in the available time. Thus, this mechanism is primarily relevant when there is an external time limit or when concurrent demands such as a secondary task are present (corresponding to age-related decline in sequence learning under dual-task conditions; see Frensch & Miner, 1994; Nejati et al., 2008). The simultaneity mechanism is based on the assumption that the products of early processing may be lost by the time that later processing is completed. That is, the slowing reduces the amount of simultaneously available information.

The processing speed theory has been applied previously to account for the deficit in sequence learning in older adults (cf., Willingham, 1998). We propose that it can also be applied to account for developmental differences in sequence learning in childhood. In line with previous studies (e.g., Fischer et al., 2007; Karatekin et al., 2007; Meulemans et al., 1998; Thomas et al., 2004), children responded more slowly than young adults but did not differ from older adults. According to the processing speed theory, incidental sequence learning in children may be impaired because the sequence information may not be available long enough to integrate across several elements. Furthermore, the differential findings of participants with complete explicit knowledge and those with little explicit knowledge may be related to differences in the speed of processing as well. Across all age groups, participants with explicit knowledge responded faster than those without explicit knowledge. Hence, processing speed may have been more constraining in participants without explicit knowledge.

A different account for age-related differences in cognition has been proposed by Craik and Bialystok (2006). They suggested that lifelong changes are attributable to processes concerned with cognitive representation, control, and their interaction. Representations are defined as the set of crystallized schemas that represent the basis for memory and knowledge. Control is defined as the set of fluid operations that enable intentional processing and adaptive cognitive performance (Craik & Bialystok, 2006). Both processes and their interaction evolve across the lifespan and determine cognitive ability. Representational knowledge is assumed to increase during childhood, to further accumulate throughout adulthood and to remain relatively stable in old age. In contrast, cognitive control is assumed to increase in power, speed and complexity from childhood to young adulthood, and to decline thereafter. Additionally, age-related changes in sensory and motor processes affect cognitive development and decline.

The account of Craik and Bialystok (2006) can explain the age-related differences found in the present study because children differ from young adults with regard to their representational systems. These systems are hierarchically organized, with general, conceptual knowledge at higher levels (e.g., tasks or stimulus categories used in the present study) and specific category exemplars at lower levels (e.g., the specific stimulus exemplars). Children have direct access to concrete lower-level representations and build up higher-level representations gradually. Thus, developmental differences in task sequence learning may be related to differences in the representation of higher-level information because the sequenced information is embedded within these higher-level information rather than within the order of the specific stimulus exemplars. In contrast, the observed impairment in older adults may be related to the decline in control processes which may produce a deficit in the integration of new information.

4.4. Conclusions

In sum, the present findings suggest that children and older adults are impaired at incidental sequence learning. Although incidental sequence learning seemed to be age-invariant at first glance, a closer look at participants with little or no explicit sequence knowledge revealed age-related differences. The absence of incidental sequence learning without conscious awareness in children and older adults indicates that incidental learning of complex sequenced information is affected both by developmental change in childhood and by cognitive aging in adulthood. The investigation of children and older adults with the same paradigm is a first step to close to gap between developmental and aging studies. However, future research is needed to draw a clearer picture of lifelong changes in incidental sequence learning and to achieve a more thorough understanding of the underlying processes. For example, the different age groups might be further subdivided and middle-aged adults could be included. Furthermore, the investigation of the time course of learning by incorporating random probes in each block could reveal more subtle age-related differences in incidental sequence learning.

Acknowledgements

We thank Geneviève Beer, Melanie Brudermann, Claudia Buser, Lea Huber, Gabriela Jost, Stéphanie Loher, Francine von Weissenfluh, Olivia Wagner, Maurizia Walzthöny, and Christina Wild for data collection, and Alodie Rey-Mermet for valuable comments on an earlier version of the manuscript. This work was supported by the Swiss National Science Foundation (Grant 130104 to B. Meier).

References

Aizenstein, H. J., Butters, M. A., Clark, K. A., Figurski, J. L., Stenger, V. A., Nebes, R. D., et al. (2006). Prefrontal and striatal activation in elderly subjects during concurrent implicit and explicit sequence learning. *Neurobiology of Aging, 27*, 741–751.

Asato, M. R., Terwilliger, R., Woo, J., & Luna, B. (2010). White matter development in adolescence: A DTI study. *Cerebral Cortex, 20*, 2122–2131.

Baltes, P. B. (1987). Theoretical propositions of life-span developmental psychology: On the dynamics between growth and decline. *Developmental Psychology, 23*, 611–626.

Cock, J., & Meier, B. (2007). Incidental task sequence learning: Perceptual rather than conceptual? *Psychological Research, 71*, 140–151.

Craik, F. I. M., & Bialystok, E. (2006). Cognition through the lifespan: Mechanisms of change. *Trends in Cognitive Sciences, 10*, 131–138.

Curran, T. (1997). Effects of aging on implicit sequence learning: Accounting for sequence structure and explicit knowledge. *Psychological Research, 60*, 24–41.

Daselaar, S. M., Rombouts, S. A., Veltman, D. J., Raaijmakers, J. G., & Jonker, C. (2003). Similar network activated by young and old adults during the acquisition of a motor sequence. *Neurobiology of Aging, 24*, 1013–1019.

De Guise, E., & Lassonde, M. (2001). Callosal contribution to procedural learning in children. *Developmental Neuropsychology, 19*, 253–272.

Dennis, N. A., & Cabeza, R. (2011). Age-related dedifferentiation of learning systems: An fMRI study of implicit and explicit learning. *Neurobiology of Aging,* 32, 2318.e17–2318.230.

Dennis, N. A., Howard, J. H., Jr., & Howard, D. V. (2003). Age deficits in learning sequences of spoken words. *Journals of Gerontology: Psychological Sciences, 58*, P224–P227.

Dennis, N. A., Howard, J. H., & Howard, D. V. (2006). Implicit sequence learning without motor sequencing in young and old adults. *Experimental Brain Research, 175*, 153–164.

Destrebecqz, A., Peigneux, P., Laureys, S., Degueldre, C., Del Fiore, G., Aerts, J., et al. (2005). The neural correlates of implicit and explicit sequence learning: Interacting networks revealed by the process dissociation procedure. *Learning and Memory, 12*, 480–490.

Dienes, Z. (2008). Subjective measures of unconscious knowledge. In R. Banerjee & B. Chakrabarti (Eds.). *Progress in brain research* (Vol. 168, pp. 49–64). Amsterdam, The Netherlands: Elsevier.

Exner, C., Koschack, J., & Irle, E. (2002). The differential role of premotor frontal cortex and basal ganglia in motor sequence learning: Evidence from focal basal ganglia lesions. *Learning and Memory, 9*, 376–386.

Feeney, J. J., Howard, J. H., Jr., & Howard, D. V. (2002). Implicit learning of higher order sequences in middle age. *Psychology and Aging, 17*, 351–355.

Fischer, S., Wilhelm, I., & Born, J. (2007). Developmental differences in sleep's role for implicit off-line learning: Comparing children with adults. *Journal of Cognitive Neuroscience, 19*, 214–227.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). Mini-mental state: A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatry Research, 12*, 189–198.

Frensch, P. A., & Miner, C. S. (1994). Effects of presentation rate and individual differences in short-term memory capacity on an indirect measure of serial learning. *Memory and Cognition, 22*, 95–110.

Gaillard, V., Destrebecqz, A., Michiels, S., & Cleeremans, A. (2009). Effects of age and practice in sequence learning: A graded account of ageing, learning, and control. *European Journal of Cognitive Psychology, 21*, 255–282.

Giedd, J. N., Blumenthal, J., Jeffries, N. O., Castellanos, F. X., Liu, H., Zijdenbos, A., et al. (1999). Brain development during childhood and adolescence: A longitudinal MRI study. *Nature Neuroscience, 2*, 861–863.

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., et al. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *PNAS, 101*, 8174–8179.

Gómez Beldarrain, M., Grafman, J., Pascual-Leone, A., & Garcia-Monco, J. C. (1999). Procedural learning is impaired in patients with prefrontal lesions. *Neurology, 52*, 1853–1860.

Gómez Beldarrain, M., Grafman, J., Ruiz de Velasco, I., Pascual-Leone, A., & Garcia-Monco, J. C. (2002). Prefrontal lesions impair the implicit and explicit learning of sequences of visuomotor tasks. *Experimental Brain Research, 142*, 529–538.

Gotler, A., Meiran, N., & Tzelgov, J. (2003). Nonintentional task set activation: Evidence from implicit task sequence learning. *Psychonomic Bulletin and Review, 10*, 890–896.

Grafton, S. T., Hazeltine, E., & Ivry, R. (1995). Functional mapping of sequence learning in normal humans. *Journal of Cognitive Neuroscience, 7*, 497–510.

Grafton, S. T., Hazeltine, E., & Ivry, R. B. (1998). Abstract and effector-specific representations of motor sequences identified with PET. *Journal of Neuroscience, 18*, 9420–9428.

Harrington, D. L., & Haaland, K. Y. (1992). Skill learning in the elderly: Diminished implicit and explicit memory for a motor sequence. *Psychology and Aging, 7*, 425–434.

Hazeltine, E., Grafton, S. T., & Ivry, R. (1997). Attention and stimulus characteristics determine the locus of motor-sequence encoding. A PET study. *Brain, 120*, 123–140.

Hedden, T., & Gabrieli, D. E. (2004). Insights into the ageing mind: A view from cognitive neuroscience. *Nature Reviews Neuroscience, 5*, 87–96.

Heuer, H., Schmidtke, V., & Kleinsorge, T. (2001). Implicit learning of sequences of tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 967–983.

Howard, D. V., & Howard, J. H. (1989). Age differences in learning serial patterns: Direct versus indirect measures. *Psychology and Aging, 4*, 357–364.

Howard, D. V., & Howard, J. H. (1992). Adult age differences in the rate of learning serial patterns: Evidence from direct and indirect tests. *Psychology and Aging, 7*, 232–241.

Howard, J. H., & Howard, D. V. (1997). Age differences in implicit learning of higher order dependencies in serial patterns. *Psychology and Aging, 12*, 634–656.

Howard, D. V., & Howard, J. H. (2001). When it does hurt to try: Adult age differences in the effects of instructions on implicit pattern learning. *Psychonomic Bulletin and Review, 8*, 798–805.

Howard, J. H., Howard, D. V., Dennis, N. A., Yankovich, H., & Vaidya, C. J. (2004). Implicit spatial contextual learning in healthy aging. *Neuropsychology, 18*, 124–134.

Howard, D. V., Howard, J. H., Japikse, K., DiYanni, C., Thompson, A., & Somberg, R. (2004). Implicit sequence learning: Effects of level of structure, adult age, and extended practice. *Psychology and Aging, 19*, 79–92.

Karatekin, C., Marcus, D. J., & White, T. (2007). Oculomotor and manual indexes of incidental and intentional spatial sequence learning during middle childhood and adolescence. *Journal of Experimental Child Psychology, 96*, 107–130.

Kim, J. S., Reading, S. A., Brashers-Krug, T., Calhoun, V. D., Ross, C. A., & Pearlson, G. D. (2004). Functional MRI study of a serial reaction time task in Huntington's disease. *Psychiatry Research, 131*, 23–30.

Koch, I. (2001). Automatic and intentional activation of task sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 1474–1486.

Koch, I., Philipp, A. M., & Gade, M. (2006). Chunking in task sequences modulates task inhibition. *Psychological Science, 17*, 346–350.

Lehrl, S., Merz, J., Burkhard, G., & Fischer, B. (1991). *MWT-A: Mehrfachwahl-Wortschatz-Intelligenztest. Parallelform zum MWT-B*. Erlangen: Perimed.

Lenroot, R. K., & Giedd, J. N. (2006). Brain development in children and adolescents: Insights from anatomical magnetic resonance imaging. *Neuroscience and Biobehavioral Reviews, 30*, 718–729.

Li, S., & Baltes, P. B. (2006). Cognitive developmental research from lifespan perspectives: The challenge of integration. In E. Bialystok & F. I. M. Craik (Eds.), *Lifespan cognition: Mechanisms of change* (pp. 344–363). Oxford: University Press.

Meier, B., & Cock, J. (2010). Are correlated streams of information necessary for implicit sequence learning? *Acta Psychologica, 133*, 17–27.

Meulemans, T., Van der Linden, M., & Perruchet, P. (1998). Implicit sequence learning in children. *Journal of Experimental Child Psychology, 69*, 199–221.

Nejati, V., Garusi Farshi, M. T., Ashayeri, H., & Aghdasi, M. T. (2008). Dual task interference in implicit sequence learning by young and old adults. *International Journal of Geriatric Psychiatry, 23*, 801–804.

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology, 19*, 1–32.

Paus, T. (2005). Mapping brain maturation and cognitive development during adolescence. *Trends in Cognitive Sciences, 9*, 60–68.

Perruchet, P., & Amorim, M.-A. (1992). Conscious knowledge and changes in performance in sequence learning: Evidence against dissociation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*, 785–800.

Rauch, S. L., Whalen, P. J., Savage, C. R., Curran, T., Kendrick, A., Brown, H. D., et al. (1997). Striatal recruitment during an implicit sequence learning task as measured by functional magnetic resonance imaging. *Human Brain Mapping, 5*, 124–132.

Regard, M. (1981). Cognitive rigidity and flexibility: A neuropsychological study. Unpublished Ph.D. dissertation, University of Victoria.

Rieckmann, A., & Bäckman, L. (2009). Implicit learning in aging: Extant patterns and new directions. *Neuropsychology Review, 19*, 490–503.

Rieckmann, A., Fischer, H., & Bäckman, L. (2010). Activation in striatum and medial temporal lobe during sequence learning in younger and older adults: Relations to performance. *Neuroimage, 50*, 1303–1312.

Rünger, D., & Frensch, P. A. (2010). Defining consciousness in the context of incidental sequence learning: Theoretical considerations and empirical implications. *Psychological Research, 74*, 121–137.

Salthouse, T. A. (1985). *A theory of cognitive aging*. Amsterdam: North-Holland.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*, 403–428.

Salthouse, T. A. (2010). Selective review of cognitive ageing. *Journal of the International neuropsychological Society, 16*, 754–760.

Salthouse, T. A., McGuthry, K. E., & Hambrick, D. Z. (1999). A framework for analyzing and interpreting differential aging patterns: Application to three measures of implicit learning. *Aging, Neuropsychology, and Cognition, 6*, 1–18.

Savion-Lemieux, T., Bailey, J. A., & Penhune, V. B. (2009). Developmental contributions to motor sequence learning. *Experimental Brain Research, 195*, 293–306.

Shanks, D. R., & St. John, M. F. (1994). Characteristics of dissociable human learning systems. *Behavioral and Brain Sciences, 17*, 367–447.

Siegert, R. J., Taylor, K. D., Weatherall, M., & Abernethy, D. A. (2006). Is implicit sequence learning impaired in Parkinson's disease? A meta-analysis. *Neuropsychology, 20*, 490–495.

Simon, J. R., Vaidya, C. J., Howard, J. H., Jr., & Howard, D. V. (2012). The effects of aging on the neural basis of implicit associative learning in a probabilistic triplets learning task. *Journal of Cognitive Neuroscience, 24*, 451–463.

Sowell, E. R., Thompson, P. M., Holmes, C. J., Jernigan, T. L., & Toga, A. W. (1999). In vivo evidence for post-adolescent brain maturation in frontal and striatal regions. *Nature Neuroscience, 2*, 859–861.

Sowell, E. R., Trauner, D. A., Gamst, A., & Jernigan, T. L. (2002). Development of cortical and subcortical brain structures in childhood and adolescence: A structural MRI study. *Developmental Medicine and Child Neurology, 44*, 4–16.

Tewes, U. (2001). *Hamburg-Wechsler Intelligenztest für Erwachsene, Revision 1991, HAWIE-R*. Bern: Huber.

Thomas, K. M., Hunt, R. H., Vizueta, N., Sommer, T., Durston, S., Yang, Y., et al. (2004). Evidence of developmental differences in implicit sequence learning: An fMRI study of children and adults. *Journal of Cognitive Neuroscience, 16*, 1339–1351.

Thomas, K. M., & Nelson, C. A. (2001). Serial reaction time learning in preschool- and school-age children. *Journal of Experimental Child Psychology, 79*, 364–387.

Toga, A. W., Thompson, P. M., & Sowell, E. R. (2006). Mapping brain maturation. *Trends in Neurosciences, 29*, 148–159.

Vakil, E., Kahan, S., Huberman, M., & Osimani, A. (2000). Motor and non-motor sequence learning in patients with basal ganglia lesions: The case of serial reaction time (SRT). *Neuropsychologia, 38*, 1–10.

Weiermann, B., Cock, J., & Meier, B. (2010). What matters in implicit task sequence learning: Perceptual stimulus features, task-sets, or correlated streams of information? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 1492–1509.

Willingham, D. B. (1998). Implicit learning and motor skill learning in older subjects. An extension of the processing speed theory. In M. A. Stadler & P. A. Frensch (Eds.), *Handbook of implicit learning* (pp. 573–594). Thousand Oaks, London, New Delhi: SAGE Publications.

Yates, J. F. (1994). Subjective probability accuracy analysis. In G. Wright & P. Ayton (Eds.), *Subjective probability* (pp. 381–410). Chichester, England: Wiley.

Zimmermann, T. D., & Meier, B. (2006). The rise and decline of prospective memory performance across the lifespan. *Quarterly Journal of Experimental Psychology, 59*, 2040–2046.